Particle Accelerators

A DEVICE that provides forces on charged particles by some combination of electric and magnetic fields and brings the ions to high speed and kinetic energy is called an accelerator. Many types have been developed for the study of nuclear reactions and basic nuclear structure, with an ever increasing demand for higher particle energy. In this chapter we shall review the nature of the forces on charges and describe the arrangement and principle of operation of several important kinds of particle accelerators. In later chapters we describe some of the many applications.

In additional, we can see that: All accelerators use electromagnetic forces to boost the energy of stable charged particles. These are injected into the machine from a device that provides a high intensity source of low-energy particles, for example an electron gun (a hot filament), or a proton ion source. The accelerators used for nuclear structure studies may be classified into those that develop a steady accelerating field (DC machines) and those in which radio frequency electric fields are used (AC machines). All accelerators for particle physics are of the latter type. We will start later on with a brief description of DC machines.

The sources-accelerators that can be used to obtain energetic charged particles, and secondarily neutrons and photons, that can induce nuclear reactions or chemical changes. Thus we include various accelerators for producing beams of charged particles as well as neutrons. Electrons can be accelerated by the same principles as positive ions but in the following paragraphs we will focus on the acceleration of positive ions because these are more useful for nuclear reactions. Although accelerators can be used to produce neutrons, a more copious neutron source is the nuclear reactor. Small neutron sources, consisting of the spontaneous fissioning nuclide ^{252}Cf or of mixtures of elements like radium and beryllium in which nuclear transmutations (mostly (α,n)-reactions) produce neutrons.

Charged Particle Accelerators

In order to induce nuclear reactions with positively charged projectiles such as protons, deuterons, α-particles, oxygen ions, or uranium ions, it is necessary that the projectile particles have sufficient kinetic energy to overcome the Coulomb barrier created by the repulsion between the positive charges of the projectile and the nucleus. While there is some probability that a positive projectile can tunnel through the Coulomb barrier at kinetic energies lower than the maximum value of

the barrier, this probability is quite small until the kinetic energy is close to the barrier maximum.

In 1919 Rutherford caused artificial transmutation of one element into another by using as projectiles the α-particles emitted in the radioactive decay of ^{214}Po. These α-particles had sufficient kinetic energy (7.7 MeV) upon emission from the polonium nucleus to overcome the Coulomb barrier and react with nitrogen nuclei. However, the kinetic energy of α-particles emitted in radioactive decay is insufficient to overcome the Coulomb barrier to react with nuclei of higher atomic numbers. Consequently, means had to be devised for acceleration of the charged projectiles to kinetic energies sufficient to achieve reaction.

The principle to be used to achieve the higher kinetic energies was obvious. The projectile particles would have to be ionized to obtain positively charged ions. If these ions could be accelerated through a potential difference of 1000 V, they would acquire 1000 eV additional kinetic energy, per unit of charge. If an α-particle of a +2 charge was to be accelerated through a potential difference of 10^6 V, it would acquire an additional kinetic energy or 2 MeV.

The problem of obtaining the desired kinetic energy involved two aspects: first, the production of the charged particles: second, the acceleration through the necessary potential difference, where both nuclear and particle physics experiments are typically performed at accelerators, where particles are accelerated to extremely high energies, in most cases relativistic (i.e., $v \approx c$).

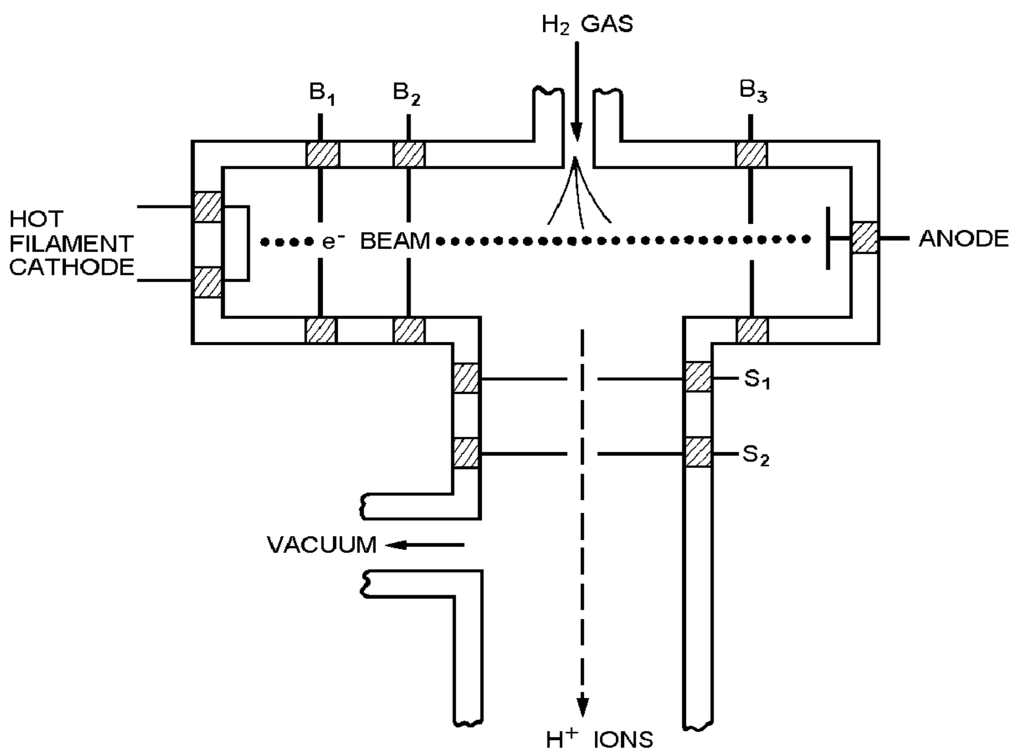
Target

There are two ways to make the necessary collisions with the accelerated beam: Fixed target and colliding beams. In fixed target mode the accelerated beam hits a target which is fixed in the laboratory. In the case of colliding beams we use the fact that we have (say) an electron beam moving one way, and a positron beam going in the opposite direction.

Ion Source

The problem of producing the positive ions is in principle relatively simple. If a gas is bombarded by energetic electrons, the atoms of the gas are ionized and positive ions produced, the next figure shows a simple ion source.

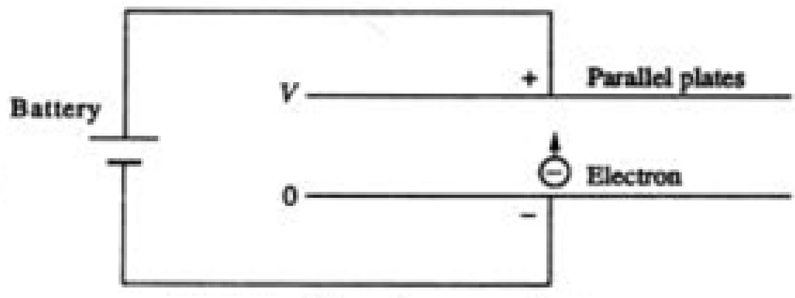
As hydrogen gas flows into the region above the filament, the electrons being emitted by the filament are accelerated to an anode (a typical voltage drop over the electrodes B_1 - B_2 may be 100 V) and in theirpassage through the gas cause ionization.



The positive ions are extracted by attraction to a negative electrode (the voltage drop over S_1 - S_2 may be 1 - 10 kV) into the accelerator region. The vacuum at the beam extraction is of the order 10^{-4} Pa but in the ionization compartment it is normally 10^{-2} Pa. The basic principle, bombardment with electrons, is similar in the different types of ion sources that have been developed to meet the demands of the variety of ions and accelerator types in use. High ion currents of all elements in a variety of charge states can now be produced.

Electric and Magnetic Forces

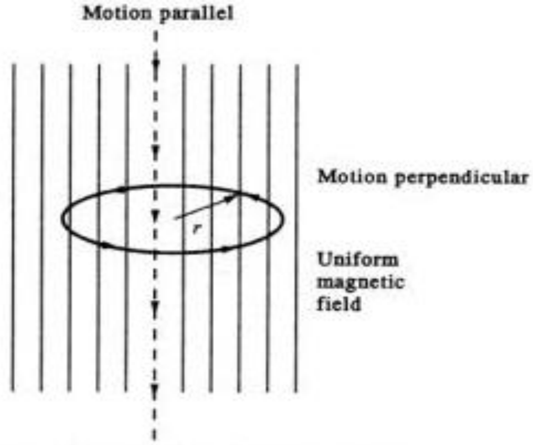
Let us recall how charged particles are influenced by electric and magnetic fields. First, visualize a pair of parallel metal plates separated by a distance d as in the sample capacitor shown in next figure. A potential difference V and electric field $\zeta = V/d$ are provided to the region of low gas pressure by a direct current voltage supply such as a battery. If an electron of mass m and charge e is released at the negative plate, it will experience a force ζe, and its acceleration will be $\zeta e/m$.



Capacitor as accelerator.

It will gain speed, and on reaching the positive plate it will have reached a kinetic energy $\frac{1}{2}\ mv^2\ = Ve$ .Thus its speed is $v = \sqrt{2Ve\ /\ m}$. For example, if V is 100 volts, the speed of an electron (m = $9.1\times\ 10^{-31}$ kg and e = 1.60×10^{-19} coulombs) is found to be $5.9\times\ 10^{6}$ m/s.

Next, let us introduce a charged particle of mass m, charge e, and speed v into a region with uniform magnetic field B, as in next figure. If the charge enters in the direction of the field lines, it will not be affected, but if it enters perpendicularly to the field, it will move at constant speed on a circle. Its radius, called the radius of gyration, is r = mv/eB, such that the stronger the field or the lower the speed, the smaller will be the radius of motion. Let the angular speed be ω (omega) equal to v/r.



Electric charge motion in uniform magnetic field.

Using the formula for r, we find ω = eB/m. If the charge enters at some other angle, it will move in a path called a helix, like a wire door spring.